August 31, 2015

Charmed baryons on the lattice

M. Padmanath[1]

Institute of Physics, University of Graz,
8010 Graz, Austria

Nilmani Mathur

Department of Theoretical Physics,
Tata Institute of Fundamental Research, Mumbai, India.

We discuss the significance of charm baryon spectroscopy in hadron physics and review the recent developments of the spectra of charmed baryons in lattice calculations. Special emphasis is given on the recent studies of highly excited charm baryon states. Recent precision lattice measurements of the low lying charm and bottom baryons are also reviewed.

PRESENTED AT

The 7th International Workshop on Charm Physics
(CHARM 2015)
Detroit, MI, 18-22 May, 2015

[1]Speaker

1 Introduction

Charmed hadrons play an important role in understanding the dynamics of QCD, the theory of strong interactions. The presence of quarks with masses significantly greater than Λ_{QCD} provides a flavor tag, which could help in understanding the mechanism of confinement and the systematics of hadron resonances that are obscure due to the chiral dynamics in light baryons. Charmonia and charmed mesons have been studied comprehensively both theoretically and experimentally [1]. However, charmed baryons have received substantially less attention, although they can provide similar insight into the nature of QCD.

The triply charmed baryon is expected to be the ideal candidate for understanding the dynamics inside the baryons, as pointed out by Bjorken several years ago [2]. With no valence light quarks, the spectra of these baryons can reveal information on the interplay between the non-perturbative and perturbative effects, and thus can elucidate our knowledge about the nature of strong interactions. On the theoretical side, the constituent quark models are expected to describe the properties of the low lying spectrum of triply charmed baryons. However, for the excited states this description becomes more unclear. There are no experimental observation of triply charmed baryons, although QCD predicts existence of such states.

The excited spectra of **doubly charmed baryons** and their splittings can shed light into their intrinsic collective degrees of freedom, which are characterized by two widely separated scales : the low momentum scale of the light quark ($\sim \Lambda_{QCD}$) and the relatively heavy charm quark mass, giving rise to excitations in these systems. Only SELEX collaboration has reported discovery of doubly charmed baryons [3]. However, these states have not been observed either by BaBar [4], Belle [5] in e^+e^- annihilation experiments, FOCUS in photo-production experiments [6], or very recently by LHCb at baryon-baryon collider experiments at CERN [7]. The helicity angular distribution analysis by SELEX suggests that an isospin splitting of ∼17 MeV for the ground state Ξ_{cc}^+ baryon, which is unusually large in comparison with the numbers for light, strange and singly charmed baryons. Such a large isospin splitting could be explained by a larger Coulombic interaction than the strong interaction [8]. However, such interaction limits the size of doubly charmed systems to unusually compact dimensions. Thus there is no precise understanding of this unusually large isospin splittings observed for doubly charmed baryons.

Single charmed baryons can guide the investigations of diquark correlations, the effective degrees of freedom to describe the dynamics inside baryons. In the light baryons, such investigations are difficult as the three diquark correlations in them follow similar dynamics. In the presence of a charm quark, one expects the difference between the diquark correlations within the light quark pair and heavy-light pair to reflect in the excited state spectra, decays, branching ratios and the production rates of charmed baryons [9]. Thus excited spectra of these systems can shed light into the

collective modes in these systems and give insight on freezing degrees of freedom, if it happens at all, and the missing baryon resonances. Thus, a systematic study of these excitations as a function of quark masses can aid in understanding the energy spectra of baryons from light to bottom, including hyperons and charmed baryons. Out of ∼17 known singly charmed baryons (with *** or more), the quantum numbers for only few excitations are known from experiments, while most of the assignments are quark model expectations [10]. Prospects for singly charmed baryons also come from finite temperature lattice studies of partial pressures of heavy-light hadrons across the deconfinement crossover [11]. They find significant contribution from additional charmed baryon states over an estimate from experimentally known excitations.

The wealth of prospects from charmed baryon spectroscopy described above and the anticipated large sets of statistical samples being collected at dedicated experiments, at J-PARC, LHCb experiment, future PANDA experiment at the FAIR facility, Belle II at KEK and BES III, which could provide lots of information on charmed baryons, calls for a quantitative understanding of the charmed baryon spectra using non-perturbative first principles calculations such as lattice QCD. All results from such lattice calculations can provide crucial inputs to the future experimental discovery. Charmed baryons have also been studied theoretically by non-relativistic and relativistic potential models, effective field theories with potential NRQCD, heavy quark spin symmetry, etc. A review of such calculations can be found in the Ref. [12]. Lattice calculations would also be important to compare with the results from these effective field theories and understand the dominant interactions that gives rise to the observed spectra.

2 Low lying spectra

Lattice QCD computations provide a powerful tool to perform ab-initio calculations of the QCD spectra and so to learn about the non-perturbative low energy regime of QCD. Over the past few years there has been remarkable progress towards simulations with physical quark masses, with many ground state hadron observables being measured with an impressive statistical precision and full control over the systematic uncertainties [13]. Lattice computation of hadron masses proceeds through the calculation of the Euclidean two point correlation functions between creation operators ($\bar{O}_i$) at time t_i and annihilation operators (O_j) at time t_f.

$$C_{ji}(t_f - t_i) = \langle 0|O_j(t_f)\bar{O}_i(t_i)|0\rangle = \sum_n \frac{Z_i^{n*} Z_j^n}{2E_n} e^{-E_n(t_f - t_i)}, \tag{1}$$

where E_n is the energy of the n^{th} excited state. The spectral information are extracted from the overlap factors (Z_j^n) for one or more two point correlation functions. Typical charmed baryon operators consist of three quark fields ($\epsilon_{abc}q^a q^b q^c$), with at least one of them being charm. Although all the lattice calculations follow this general

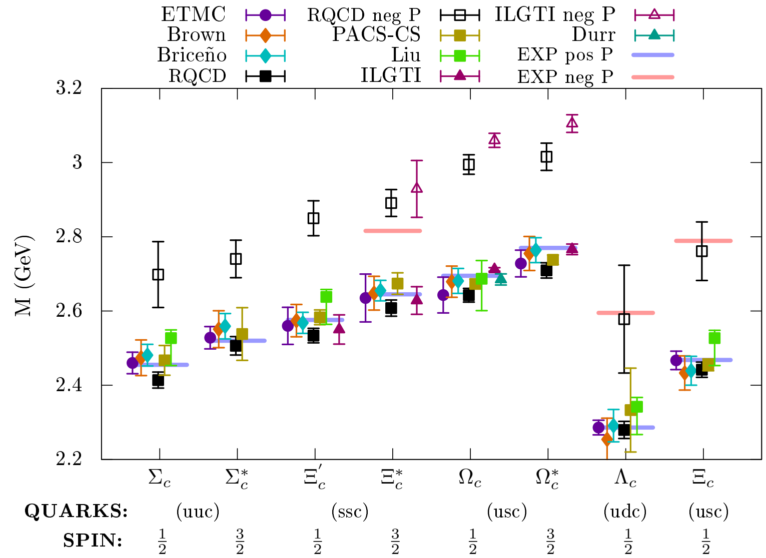


Figure 1: Compendium (Ref. [14]) of low lying singly charmed baryon states from ETMC [15], Brown *et al.*, [16], Briceño *et al.*, [17], RQCD [14], PACS-CS [18], Liu *et al.*, [19], ILGTI [20] and Dürr *et al.*, [21]. The results for a given baryon are ordered along the horizontal direction such that moving from right to left the estimates possess better knowledge of its systematic uncertainties. Details of the systematics addressed in different calculations are briefed in the text.

procedure, there are important differences in the formulations that could lead to different systematic errors. Consistency between various formulations gives confidence in the results.

In Fig. (1), a summary of the recent lattice results for the singly charmed baryon ground states has been shown. The results have been ordered along the horizontal direction for each charmed baryon such that going from right to left the estimation possess better knowledge of its systematic uncertainties. Of all the lattice systematics, chiral and continuum extrapolation are the most important for the charmed baryon ground states. Starting from left : violet circle ETMC [15] is a fully dynamical calculation on 2+1+1 flavor gauge ensembles using twisted mass fermion discretization, with chiral and continuum extrapolated results; brown diamond (Brown *et al.* [16]) and cyan diamond (Briceño *et al.*, [17]) are mixed action calculations with chiral and continuum extrapolated estimates. These chiral extrapolations follow Heavy Hadron Chiral Perturbation Theory (HHχPT) allowing not only the lattice determination of the spectrum but also the low energy constants from the effective field theory. For other numbers in the plot, either one of these two systematics has not been addressed. However, a consistency between all the lattice estimates gives confidence and with the increasing computing infrastructure

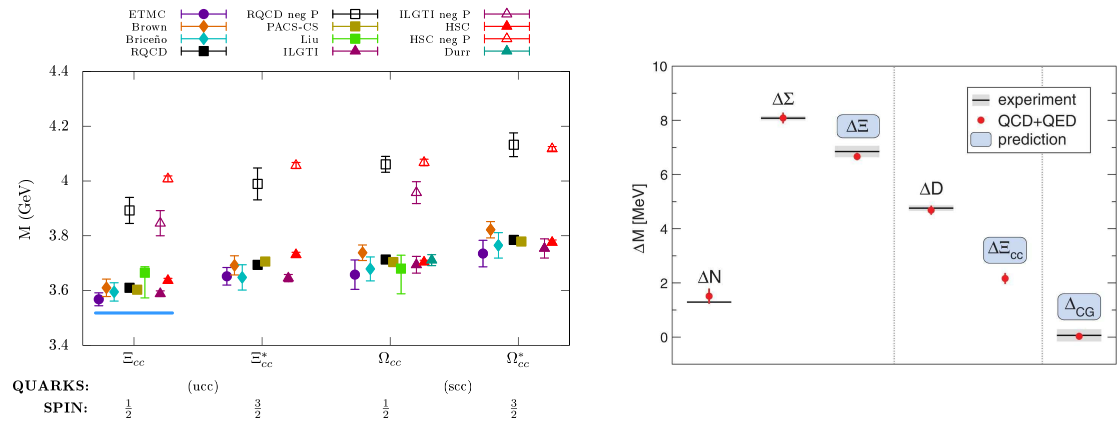


Figure 2: Left : Summary (Ref. [14]) of the low lying doubly charmed baryon states. Details are the same as in Figure 1. Right : Isospin mass splittings of light and charmed hadrons that are stable under strong and electromagnetic interactions by BMW collaboration [22]. Details in the text.

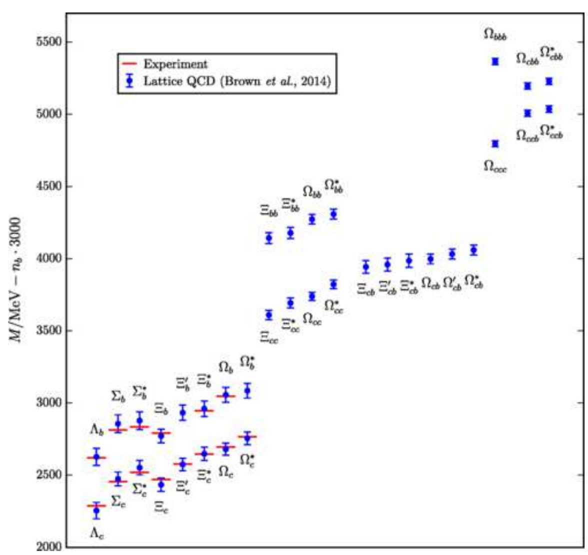


Figure 3: Summary of the lattice determination of charm and/or bottom baryons (along with experimental candidates, whichever known.) by Brown *et al* [16]. Masses of baryons with n_b bottom quarks are shown with an offset of $-n_b$. 3 GeV.

the systematic uncertainties will be pinned down to a level of experimental precision.

In the left of Fig. (2), a summary of the recent lattice results for the doubly charmed ground states are shown. The details of the systematics are the same as that in Fig. (1). All lattice estimates consistently predict the position of the low lying Ξ_{cc} baryon to be $\sim$80 MeV above the experimentally claimed value [3]. This raises questions about its discovery. On the right of Fig. (2) we show the fully controlled 1+1+1+1 flavor ab initio QCD+QED lattice determination (BMW [22]) of the isospin mass splittings for low lying light and charmed hadrons that are stable under strong and electromagnetic interactions. A value somewhat different from the physical isospin splitting for nucleons would have resulted in a completely different universe from that of ours. The precise determination of the nucleon

isospin splitting with fully controlled systematic uncertainties makes this calculation unique. They estimate the isospin splitting for the ground state Ξ_{cc} baryons to be 2.16(11)(17) MeV. This again raises questions about the validity of the observations of doubly charmed baryons by SELEX with isospin splittings $\sim$17 MeV. More results from these ensembles are much awaited.

With the advent of LHCb, bottom and charmed-bottom baryons also begin receiving significant prospects. A comprehensive lattice study of charmed and/or bottom baryons were made in the past on lattices with pure gauge action [23]. In Fig. (3), we show a summary of all the charmed and/or bottom baryons as estimated from a mixed action lattice calculation with controlled systematics by Brown *et al* [16]. In the left of Fig. (4), we show the lattice determinations for the ground state triply charmed baryon with an offset of 3/2 times the mass of J/ψ meson from respective calculations.

3 Excited state spectroscopy

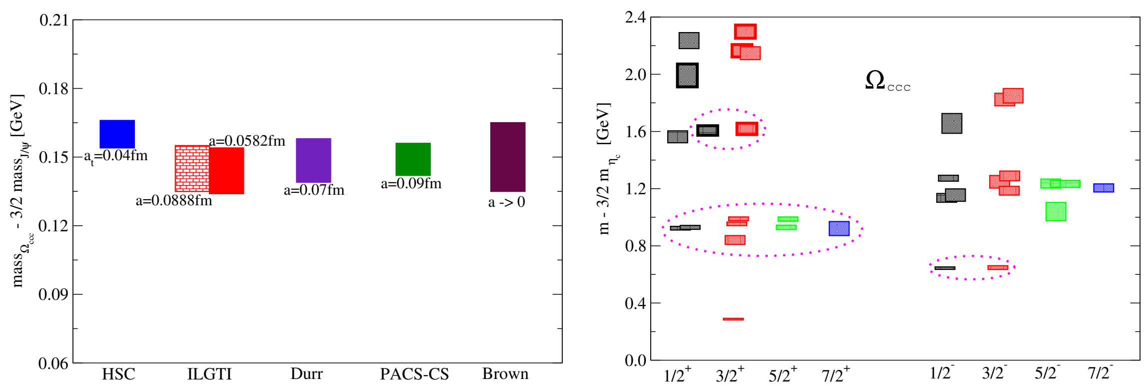
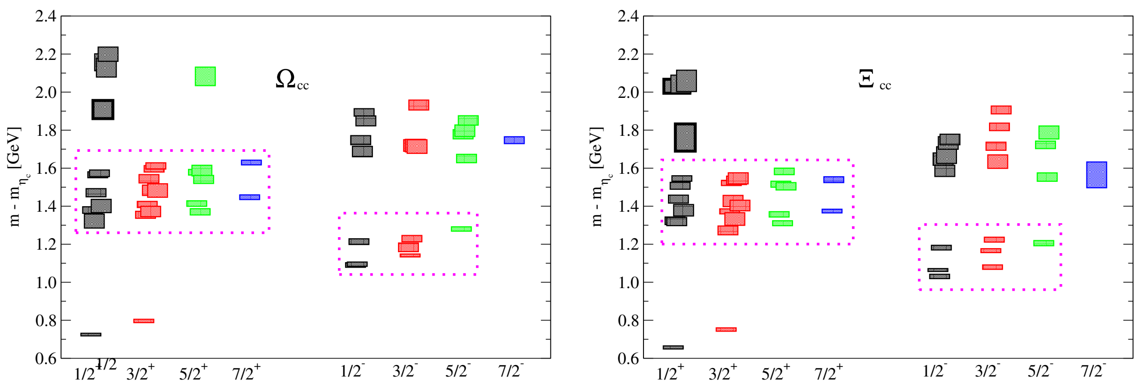


Figure 4: Left : Summary of lattice calculations of ground state triply charmed baryons from HSC [24], ILGTI [20], Dürr [21], PACS-CS [18] and Brown *et al* [16]. Right : Spin identified spectra of triply-charmed baryons with respect to $\frac{3}{2}m_{\eta_c}$ [24]. The boxes with thick borders correspond to the states with strong overlap with hybrid operators. The states inside pink ellipses are those with relatively large overlap to non-relativistic operators.

The excited state information lies in the sub-leading exponential of the spectral decomposition (eq. (1)) of the two point correlation functions. Extraction of these observables are extremely unstable by conventional spectroscopy techniques. This limits the lattice baryon investigations to the ground states with spin up to 3/2 [14, 15, 16, 17, 18, 19, 20, 21], until very recently where a comprehensive spectra of charmed baryons have been presented [24, 25]. The calculation proceeds through computation of matrix of two point correlation functions with a basis of carefully

constructed charmed baryon operators using a derivative-based operator construction formulation [26]. The operators are constructed such that they are expected to probe the radial as well as orbital excitations in the respective systems. Quark fields are also smeared to suppress the high frequency modes and to improve the overlap onto the desired low lying states. Extraction of the excited state information from the matrix of correlation functions thus computed is performed by solving the generalized eigenvalue problem, which expresses the physical states as a linear combination of the used set of interpolators. Thus using a very large basis of interpolating operators with widely different spatial structure, one can extract the ground and the excited states very reliably. Such calculations have been established in studying the light baryon spectrum [26, 27].



(a) (b)

Figure 5: Spin identified spectra of (a) Ω_{cc} and (b) Ξ_{cc} baryon for both parities and with spins up to $\frac{7}{2}$ *w.r.t.* m_{η_c} [25]. The keys are same as in right of Figure 4.

In the remaining part, we focus on the recent lattice calculation of excited charmed baryon spectra by Hadron Spectrum Collaboration (HSC) [24, 25]. With as many as 90 different interpolators for each charmed baryon, the computation of the correlation functions itself can be computationally as challenging as gauge field generation. It is to be mentioned that these calculations of excited charmed baryons are exploratory and currently lack a good control over the systematic uncertainties. Nevertheless, these calculations serve a pioneering step towards understanding baryon resonances and baryon-meson scattering. For these studies, we utilized the dynamical anisotropic gauge-field configurations generated by the Hadron Spectrum Collaboration (HSC) to extract highly excited hadron spectra. The temporal lattice spacing is $a_t^{-1} = 5.67$GeV and lattice spatial extension is $L = 1.9$ fm, which presumably is sufficiently large for charmed baryon spectroscopy. The pion mass on these lattices is 391 MeV. Further details of these lattices can be found in Refs. [28, 29].

In the right of Fig. (4) we show the spin identified spectra of the triply charmed baryons, in terms of splitting from 3/2 times m_{η_c} to account for the difference in the

charm quark content [24]. Energy splittings are in general preferred, as it reduces various systematic uncertainties. Boxes with thicker borders correspond to those states with dominant overlap onto the operators that are proportional to the field strength tensor, which might consequently be hybrid states. We classify the states within the magenta ellipses to be dominantly non-relativistic in nature due to their relatively large overlap with non-relativistic operators. One important observation is that even though we use a full relativistic plus non-relativistic set of operators, the pattern of the low lying bands exactly agree with expectations from models with an $SU(6) \otimes O(3)$ symmetry. Similar calculation of triply bottom baryons has been reported in Ref. [30].

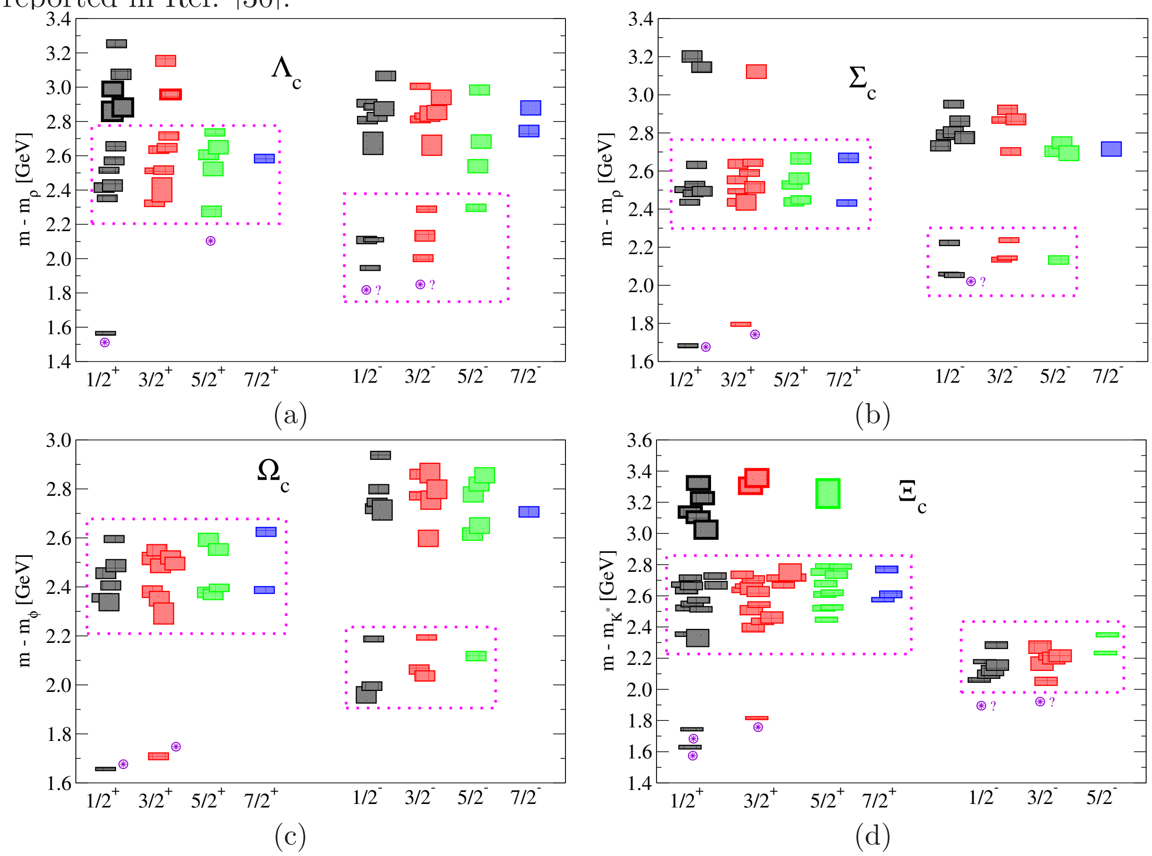


Figure 6: The spin identified spectra of (a) Λ_c, (b) Σ_c, (c) Ω_c and (d) Ξ_c baryons for both parities in terms of the splitting from the respective vector mesons. The keys are same as in the right of Figure 4.

Figure 5 shows the spin identified excited doubly charmed baryon spectra [25] as the difference from m_{η_c} to account for the difference in the charm quark content. The boxes with thick borders again represent candidates for doubly charmed baryons with strong gluonic excitations, while the states within the magenta rectangles are classified as non-relativistic in nature based on their dominant spectral overlaps. Identification

and classification of higher lying states in the third excitation band and higher are not well-defined, since the set of interpolators we use in our studies are limited to a maximum two derivatives. Once again the number and pattern of the low lying bands of the excited state spectra show consistency with prediction based on a model with SU(6)$\otimes$O(3) symmetry. The excited spectra of singly charmed baryons (Λ_c, Σ_c, Ξ_c and Ω_c) are as shown in Figure 6. The spectra for singly charmed baryons are shown as the splitting from respective light vector meson mass, so that all the plots in Figure 6 have same remnant valence charm quark content. A few of the low lying experimental candidates are also shown as violet circled stars in the respective plots for comparison. Those experimental candidates with uncertain quantum numbers are identified with a question mark '?' within the plots. The singly charmed baryon spectra also show good agreement with expectation as per a model with SU(6)$\otimes$O(3) symmetry.

4 Conclusions

The wealth of experimental and theoretical prospects in heavy baryon spectroscopy calls for urgent scientific efforts from both the fronts. In addition, in a recent lattice calculation at finite temperature, signatures for existence of many additional charmed baryon excitations, *w.r.t* what is known from experiments, have been observed. First principles calculation, such as lattice QCD, can play a significant role in predicting many charmed baryon excitations yet to be observed in experiments, in revealing the role of diquark correlations in baryons, the freezing degrees of freedom, etc.

Lattice calculations of the low lying charmed baryon states have entered an era of precision spectroscopy with multiple collaborations making full QCD simulations of charmed baryon ground states with full control over the systematic uncertainties. Compendium of lattice determinations of singly, doubly and triply charmed baryons are as shown in Figs. 1, 2 and 4. Figure 3 shows the summary of charmed, bottom and charmed-bottom baryons from a mixed action calculation reported in Ref. [16] with controlled systematics. The first fully controlled QCD+QED 1+1+1+1 flavor lattice determination of isospin splitting of the doubly charmed baryon by BMW collaboration [22] deserves special mention. They estimate this value to be 2.16(11)(17) MeV, which raises questions against the only doubly charmed candidate observed.

The first exploratory calculation of excited charmed baryon spectra has been made in Refs. [24, 25] and a controlled systematic study of excited charmed baryons is on the run. The calculations proceeds through computation of matrices of two point correlation functions of large set of interpolators and expressing the physical states as a spectral combination of these interpolators. Figs. 4, 5 and 6 show the excited spectra of charmed baryons from these calculations. The ground states from these calculations are also compared to find agreement with other lattice determinations in Figs. 2 and 4. The excited spectra that we obtain have excitations with well-

defined spins up to 7/2 for both the parities and the low lying levels resemble the expectations from a model with $SU(6) \otimes O(3)$ symmetry. However, with as many as 90 interpolators for each charmed baryons, the computation of the matrices of correlation functions are computationally as demanding as gauge field generation. It is to be mentioned that these calculations are at an exploratory level and the systematic uncertainties like chiral and continuum extrapolation and infinite volume limits have not been addressed here. However, it serves as a pioneering work towards understanding baryon resonances. Efforts are being made to include baryon-meson kind of operators to account for the possible scattering and decay of the excitations. The absence of such operators may affect some of the above conclusions, however to a lesser extent than their influence in the light hadron spectra.

A number of lattice calculations addressing the electromagnetic form factors and radiative transitions of charmed baryons, semi-leptonic form factors and exclusive decay rates of Λ_b baryons exist in literature. These subjects have not been covered in this review due to space constraint and interested readers can find the details in Refs. [31, 32].

5 Acknowledgements

We would like to thank our collaborators Robert Edwards and Mike Peardon. We also thank Paula Perez-Rubio and Sayantan Sharma for providing us material for the talk. We would also like to acknowledge Christian Lang and Stefan Meinel for discussions. Computations related to our work were done at gaggle and brood clusters of DTP,TIFR, computational facilities of ILGTI, Trinity college as well as at Jefferson Lab. NM acknowledges support from the Department of Theoretical Physics, TIFR, and MP acknowledges support from the Austrian Science Fund (FWF):[I1313-N27].

References

[1] S. Prelovsek, PoS LATTICE **2014**, 015 (2014);
S. L. Olsen, Front. Phys. China. **10**, 121 (2015).

[2] J. D. Bjorken, FERMILAB-CONF-85/69, Apr. 1985;

[3] M. Mattson *et al.* [SELEX Collaboration], Phys. Rev. Lett. **89**, 112001 (2002).

[4] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. D **74**, 011103 (2006).

[5] Y. Kato *et al.* [Belle Collaboration], Phys. Rev. D **89**, no. 5, 052003 (2014).

[6] S. P. Ratti, Nucl. Phys. Proc. Suppl. **115**, 33 (2003).

[7] R. Aaij *et al.* [LHCb Collaboration], JHEP **1312**, 090 (2013).

[8] S. J. Brodsky *et al.*, Phys. Lett. B **698**, 251 (2011).

[9] K. Shirotori *et al.*, J. Phys. Conf. Ser. **569**, no. 1, 012085 (2014).

[10] K. A. Olive *et al.* [PDG Collaboration], Chin. Phys. C **38**, 090001 (2014).

[11] A. Bazavov *et al.*, Phys. Lett. B **737**, 210 (2014).

[12] V. Crede and W. Roberts, Rept. Prog. Phys. **76**, 076301 (2013).

[13] S. Aoki *et al.*, Eur. Phys. J. C **74**, 2890 (2014);
S. Durr *et al.*, Science **322**, 1224 (2008).

[14] P. Prez-Rubio, S. Collins and G. S. Bali, Phys. Rev. D **92**, no. 3, 034504 (2015).

[15] C. Alexandrou *et al.*, Phys. Rev. D **90**, no. 7, 074501 (2014).

[16] Z. S. Brown *et al.*, Phys. Rev. D **90**, no. 9, 094507 (2014).

[17] R. A. Briceno, H. W. Lin and D. R. Bolton, Phys. Rev. D **86**, 094504 (2012).

[18] Y. Namekawa *et al.* [PACS-CS], Phys. Rev. D **87**, no. 9, 094512 (2013).

[19] L. Liu *et al.*, Phys. Rev. D **81**, 094505 (2010).

[20] S. Basak *et al.*, PoS LATTICE **2013**, 243 (2014).

[21] S. Durr, G. Koutsou and T. Lippert, Phys. Rev. D **86**, 114514 (2012).

[22] S. Borsanyi *et al.*, Science **347**, 1452 (2015).

[23] N. Mathur, R. Lewis and R. M. Woloshyn, Phys. Rev. D **66**, 014502 (2002).

[24] M. Padmanath *et al.*, Phys. Rev. D **90**, no. 7, 074504 (2014)

[25] M. Padmanath *et al.*, Phys. Rev. D **91**, no. 9, 094502 (2015).

[26] R. G. Edwards *et al.*, Phys. Rev. D **84**, 074508 (2011).

[27] R. G. Edwards *et al.* [HSC], Phys. Rev. D **87**, no. 5, 054506 (2013).

[28] R. G. Edwards, B. Joo and H. -W. Lin, Phys. Rev. D **78**, 054501 (2008).

[29] H. -W. Lin, *et al.* [HSC], Phys. Rev. D **79**, 034502 (2009)

[30] S. Meinel, Phys. Rev. D **85**, 114510 (2012).

[31] K. U. Can *et al.*, JHEP **1405**, 125 (2014) *and references therein.*

[32] S. Meinel, PoS LATTICE **2013**, 024 (2014) *and references therein.*